CONCISE ENCYCLOPEDIA OF

MAGNETIC & SUPERCONDUCTING MATERIALS

Editor

JAN EVETTS

University of Cambridge, UK

Executive Editor

ROBERT W CAHN FRS

University of Cambridge, UK

Senior Advisory Editor

MICHAEL B BEVER

MIT, Cambridge, MA, USA

PERGAMON PRESS

OXFORD • NEW YORK • SEOUL • TOKYO

UK	Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW, England
USA	Pergamon Press, Inc., 660 White Plains Road, Tarrytown, New York 10591-5153, USA
KOREA	Pergamon Press Korea, KPO Box 315, Seoul 110-603, Korea
JAPAN	Pergamon Press Japan, Tsunashima Building Annex, 3-20-12 Yushima, Bunkyo-ku, Tokyo 113, Japan

First edition 1992

Library of Congress Cataloging in Publication Data

Concise encyclopedia of magnetic & superconducting materials / editor, J. E. Evetts. — 1st ed.

p. cm. — (Advances in materials science and engineering)

Includes index.

1. Magnetic materials—Encyclopedias. 2. Superconductors—Encyclopedias. I. Evetts, J. II. Title: Concise encyclopedia of magnetic and superconducting materials. III. Series.

QC764.52.C66 1992

620.1'1297—dc20 91–37830

British Library Cataloguing in Publication Data

Evetts, J. (Jan)

Concise encyclopedia of magnetic and superconducting materials. — (Advances in materials science and engineering)

I. Title II. Series

537.622

ISBN 0–08–034722–3

Magnetic Units and Material Specification

1. Magnetic Quantities and Symbols

It was the prerogative of the nineteenth-century electromagneticians to suggest names and symbols for the magnetic quantities. Maxwell was responsible for the codification of many of these and influenced the terminology adopted by his contemporaries. He used the symbol H for the "magnetizing force," now called the magnetic field strength, and the symbol B for the magnetic induction or magnetic flux density. In this tradition, which originated with Faraday, the primary magnetic field was H. The term "magnetic induction" alluded to the status of B as a dependent variable. Thus, the "coefficient of induced magnetization" χ (called magnetic susceptibility by William Thomson in 1872) was the ratio of the magnetization M to H, not M to B, and the "coefficient of induction" μ (named permeability by Thomson) was the ratio of B to H.

This philosophy has not been universally accepted. The field within magnetized matter is not H but B; H has its source only in conduction currents while B is produced by both conduction and Amperian (atomic) currents and is therefore more general. Those emphasizing the primacy of B have an excellent point but are at a historical disadvantage. In magnetostatic problems, the magnetic pole approach has traditionally been used in direct analogy with electrostatics. Fictitious surface poles are taken as sources of H, and B is the sum of H and M. In this traditional approach, H internal to a magnetized sample originates not only from external field sources but also from the self-field of the magnetization. Therefore, H, in the equations for B that follow, is the *internal* field, equal to the external or applied field H_a corrected by the demagnetizing field H_d:

$$H = H_a + H_d$$

H_d depends on M and on the geometric demagnetizing factor N (see *Demagnetizing Factors*):

$$H_d \equiv -NM$$

Ellipsoids, including spheres, have uniform M in a uniform H_a. If H_a is along one of the principal axes, M is in the direction of H_a. For nonellipsoidal bodies, M is uniform only in the limit $\chi = 0$, applicable to weakly magnetic and saturated ferromagnetic materials. The demagnetizing factors for three orthogonal axes of any uniformly magnetized body sum to unity. For certain shapes, such as long cylinders in axial fields or toroids in azimuthal fields, $N = 0$.

The measurement of susceptibility requires the application of H_a and the measurement of M. The susceptibility dM/dH_a is characteristic of the *sample* and may be termed the *external* susceptibility χ_{ext}. The *internal* susceptibility χ, characteristic of the *material*, is dM/dH. The two susceptibilities are related:

$$\chi = \chi_{ext}/(1 - N\chi_{ext})$$
$$\chi_{ext} = \chi/(1 + N\chi)$$

2. Magnetic Units

An expression of the relationship between B, H and M is sufficient to establish the system of units in use. In the rationalized meter–kilogram–second (mks) systems, there are at least two recognized relationships, depending on whether one wishes to refer to magnetization M or to magnetic polarization J (sometimes the symbol I, for intensity of magnetization, is used):

$$B = \mu_0(H + M) \quad (1)$$

$$B = \mu_0 H + J \quad (2)$$

where μ_0 is the permeability of vacuum equal to $4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$. The structure of Eqn. (1) is such that B is analogous to the electric field E. In Eqn. (2), H is analogous to E. The word rationalized refers to the absence of the irrational number 4π in Eqns. (1) and (2) and in Maxwell's equations.

In the *Système International d'Unités* (SI), which evolved from the rationalized meter–kilogram–second–ampere (mksa) system, the defining relationship is Eqn. (1). However, magnetic polarization J is also a recognized quantity. The units of B and J are webers per square meter ($\mathrm{Wb\,m^{-2}}$) or teslas (T). The units of H and M are amperes per meter ($\mathrm{A\,m^{-1}}$), although H was sometimes expressed as ampere turns per meter in mksa.

In the Gaussian and the electromagnetic unit (emu) systems, which are unrationalized centimeter–gram–second (cgs) systems,

$$B = H + 4\pi M \quad \text{(cgs)}$$

where B is in gausses (G) and H is in oersteds (Oe) (a unit that is dimensionally and numerically equivalent to G). The magnetization, when written as $4\pi M$, is also in gausses and may be thought of as a field arising from the magnetic moment. When magnetization is expressed simply as M (the magnetic moment m per unit volume) its units are $\mathrm{erg\,G^{-1}\,cm^{-3}}$. In terms of base units, $\mathrm{erg} = \mathrm{cm^2\,g\,s^{-2}}$ and $\mathrm{G} = \mathrm{cm^{-1/2}\,g^{1/2}\,s^{-1}}$; therefore, $\mathrm{erg\,G^{-1}\,cm^{-3}}$, the units for M, are dimensionally but not numerically equivalent to G. It is often a source of confusion that $4\pi M$ and M have different units. M is conventionally expressed as $\mathrm{emu\,cm^{-3}}$. The designation "emu," however, is merely an indicator that electromagnetic units are in use; it is not a unit.

Magnetic susceptibility χ is dM/dH in both cgs and SI. In cgs, the ambiguity in the units for M extends to χ. In terms of base units, χ is a dimensionless quantity. However, χ is usually expressed as emu, $\mathrm{emu\,cm^{-3}}$ or $\mathrm{emu\,cm^{-3}\,Oe^{-1}}$. Occasionally, cgs susceptibility is written as $4\pi\chi$ (dimensionless), which is equal to SI susceptibility (dimensionless). The quantities M and χ are based on a unit volume of material. Consistent with SI, but not recognized as important SI quantities, are the mass (specific) magnetization σ and mass (specific) susceptibility χ_ρ.

Differential permeability μ is dB/dH in both cgs and SI. In cgs, it is dimensionless and

$$\mu = 1 + 4\pi\chi \quad \text{(cgs)}$$

In SI, permeability has the dimensions of μ_0. The relative permeability is defined as

$$\mu_r \equiv \mu/\mu_0 = 1 + \chi$$

and is numerically equal to cgs permeability.

The use of SI, rather than cgs, is recommended by all international standards organizations. One of its advantages is the painless unification of magnetic quantities with practical electrical units—the ampere and the volt. In comparison, the unit for current in emu is the abampere. In the Gaussian system, which uses electrostatic units (esu) for the electrical quantities, it is the statampere. Another advantage of SI is that each magnetic quantity has defined units, so that the dimensional balance of equations is always apparent. Because SI is a rationalized system, the ambiguity between M and $4\pi M$ does not occur. Disadvantages of SI for magnetics are the dual recognition of M and J, the awkward magnitudes of values for H and the fact that $\mu_0 \neq 1$. Table 1 is a list of the magnetic quantities, their accepted names and symbols, their recommended SI units and the conversion of cgs units to SI units.

Although other consistent metric systems of units are occasionally used in magnetism, the SI and cgs systems are those in common use. Some authors use "practical" units, combining length in centimeters, current in amperes and magnetic field strength in oersteds. While this might be of some utility to uncritical users of formulae, the equations do not balance dimensionally. Consequently, the haphazard use of such mixed units is discouraged. English units in electromagnetism, such as kilolines per square inch, are obsolete.

3. *Magnetic Hysteresis Loop*

The static magnetic properties of a material are represented by a plot of either magnetization or magnetic flux density as a function of field (M–H or B–H curves). Ferromagnetic materials exhibit hysteresis, a word first used by Ewing in 1881 to mean "lag behind." The volume energy dissipation per field cycle w is the area of the hysteresis loops, in units of joules per cubic meter. As shown in Fig. 1, M–H and B–H loops have different contours. For samples with a nonzero demagnetizing factor, the loop shapes will depend on whether H_a or H is plotted. Despite the different shapes of these hysteresis loops for a given sample, the energy loss is the same for each representation:

$$w = \mu_0 \oint H_a\, dM = \mu_0 \oint H\, dM = \oint H_a\, dB = \oint H\, dB$$

The following parameters are identified in Fig. 1a: saturation magnetization M_s, remanent (not "remnant") magnetization M_r and intrinsic coercivity (or intrinsic coercive force) H_{ci}, H_{cm} or ${}_mH_c$. The squareness of the loop may be represented by the ratio of M_r to M_s. The field H_s required to saturate the magnetization is not labelled. Also not labelled is the remanent coercivity H_r or ${}_rH_c$ ($H_r > H_{ci}$); when H is reduced from a value of H_r to zero, M_r is zero. As discovered by Lord Rayleigh in 1886, the M–H_a hysteresis loop of a ferromagnetic sample with a nonzero demagnetizing factor will be sheared at an angle $\tan^{-1}(1/N)$. When the H_a axis is rescaled to the internal field, the loop becomes unsheared. In either representation, the value of H_{ci} is the same.

In Fig. 1b, the parameters are remanent (or residual) induction B_r (also known as remanence or retentivity) and coercivity (or coercive force, the term used by Poisson) H_c, H_{cB}, or ${}_bH_c$. The value measured for coercivity depends on the rate at which the hysteresis loop is cycled. Static coercivity is measured with instruments such as a vibrating-sample magnetometer. Dynamic coercivity, which usually has a measured value somewhat larger than static coercivity, is measured at 50 Hz or 60 Hz with instruments such as a B–H looper. After M saturates, B is linearly proportional to H, so there is no "saturation induction" (although the term is used anyway). Note that $\chi = \chi(H)$ and $\mu = \mu(H)$. The differential permeability $\mu(H)$ is the slope of the line tangent to the curve at point (B, H); the average permeability $\bar{\mu}(H)$ is the slope of the line from the origin to point (B, H). The initial curves in Fig. 1a, b begin at the origin with the sample in a virgin state achieved by thermal or alternating-field demagnetization.

4. *Magnetic Material Specification*

Commercial magnetic materials are characterized by many of the parameters discussed previously as well as several others.

4.1 Hard Magnetic Materials

Hard magnetic materials include permanent magnets, recording media and hard ferrites. For these materials, a metallurgical attempt is made to have large H_c and B_r. A further important magnetic parameter for the specification of these materials is the maximum energy product $(BH)_{max}$ along the "demagnetization curves" in the second and fourth quadrants of the B–H loop. Ferromagnetic materials become paramagnetic above their Curie temperature T_C. In addition to T_C, the maximum operating temperature is specified. Common permanent magnets are Al–Ni–Co, rare-earth–cobalt compounds and Nd–Fe–B.

Materials used as recording media may be particulate (γ-ferric oxide, cobalt-modified γ-ferric oxide, chromium dioxide, barium ferrite, iron particles) or thin film (cobalt–nickel, cobalt–chromium, cobalt–phosphorus). These materials are read with inductive

Table 1
Magnetic quantities recognized under SI

Symbol	Quantity	SI units[a]	Conversion from Gaussian and cgs emu to SI[b]
Φ	magnetic flux	Wb, V s	1 Mx $\rightarrow 10^{-8}$ Wb
B	magnetic flux density, magnetic induction (Φ m^{-2})	T, Wb m^{-2}	1 G $\rightarrow 10^{-4}$ T
U_m	magnetic potential difference	A	1 Gb $\rightarrow 10/(4\pi)$ A
H	magnetic field strength (U_m m^{-1})	A m^{-1}	1 Oe $\rightarrow 10^3/(4\pi)$ A m^{-1}; 1 $\gamma \rightarrow 10^{-2}/(4\pi)$ A m^{-1}
m	magnetic moment	A m^2, J T^{-1}	1 erg G^{-1}[c] $\rightarrow 10^{-3}$ A m^2
M	(volume) magnetization (m m^{-3})	A m^{-1}	1 erg G^{-1} cm^{-3}[d] $\rightarrow 10^3$ A m^{-1}; 1 G $\rightarrow 10^3/(4\pi)$ A m^{-1}
σ	(mass) magnetization	A m^2 kg^{-1}	1 erg G^{-1} g^{-1}[e] $\rightarrow$ 1 A m^2 kg^{-1}
j	magnetic dipole moment ($\mu_0 m$)	Wb m	1 erg G^{-1}[c] $\rightarrow 4\pi \times 10^{-10}$ Wb m
J	magnetic polarization ($\mu_0 M$)	T, Wb m^{-2}	1 erg G^{-1} cm^{-3}[d] $\rightarrow 4\pi \times 10^{-4}$ T
χ, κ	(volume) susceptibility (M/H)	dimensionless	1 emu cm^{-3} Oe^{-1}[f] $\rightarrow 4\pi$
χ_ρ	(mass) susceptibility	m^3 kg^{-1}	1 emu g^{-1} Oe^{-1}[g] $\rightarrow 4\pi \times 10^{-3}$ m^3 kg^{-1}
χ_{mol}	(molar) susceptibility	m^3 mol^{-1}	1 emu mol^{-1} Oe^{-1}[h] $\rightarrow 4\pi \times 10^{-6}$ m^3 mol^{-1}
μ	permeability (B/H)	H m^{-1}, Wb A^{-1} m^{-1}	$1 \rightarrow 4\pi \times 10^{-7}$ H m^{-1}
μ_r	relative permeability ($\mu/\mu_0 = 1 + \chi$)	dimensionless	$\mu \rightarrow \mu_r$
w, W	(volume) energy density (BH, $\mu_0 MH$)	J m^{-3}	1 erg cm$^{-3} \rightarrow 10^{-1}$ J m^{-3}
N, D	demagnetizing factor	dimensionless	$1 \rightarrow 1/(4\pi)$

a Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry b Gaussian units are the same as cgs emu for magnetostatics; Mx = maxwell, G = gauss, Gb = gilbert, Oe = oersted, γ = gamma c Often expressed as emu d Often expressed as emu cm^{-3} e Often expressed as emu g^{-1} f Often expressed as emu cm^{-3} or as a dimensionless quantity g Often expressed as emu g^{-1} or as cm^3 g^{-1} h Often expressed as emu mol^{-1} or as cm^3 mol^{-1}

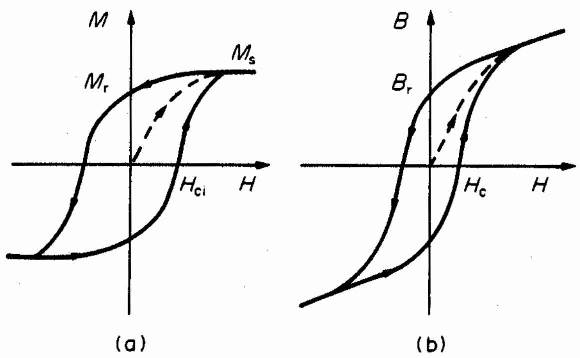

Figure 1
(a) Magnetization M and (b) magnetic flux density B as functions of magnetic field strength H (the initial curves are shown as broken lines)

or magnetoresistive heads. Important material specifications are M_r and H_c. The magnetocrystalline anisotropy constant K_u and the anisotropy field H_k,

$$H_k = 2K_u/\mu_0 M_s$$

are relevant to media with perpendicular anisotropy. Other magnetic specifications relate specifically to reading and writing performance. Another class of materials with perpendicular anisotropy is used for magnetooptic recording. These are written thermomagnetically and read using the Kerr effect (see *Magnetooptic Storage Media*). The Kerr rotation angle θ_K is specified. Typical materials are terbium–iron and Tb–Fe–Co.

4.2 Soft Magnetic Materials

Soft magnetic materials include transformer steels, ferrites, amorphous alloys and recording heads. These materials are designed to minimize hysteretic loss. Thus, H_c and B_r are small but μ is large. The important magnetic parameters for material specification are the initial permeability μ_i (μ at $B = 0$), the maximum permeability μ_{max}, B_r, H_c, M_s and T_C. Sometimes values for B are given for several values of H. Saturation magnetostriction λ_s is sometimes given. Because these materials are used in ac applications where eddy currents dissipate energy, the resistivity of the material is specified. In ac applications, permeability is a complex quantity, given by

$$\mu = \mu' + i\mu''$$

where μ' is the real (dispersive, inductive) part and μ'' is the imaginary (absorptive, resistive, loss) part. The loss tangent

$$\tan\delta \equiv \mu''/\mu'$$

is often specified at a given frequency, where δ is the phase angle between B and H. The quality factor Q is the reciprocal of $\tan\delta$. The relative loss factor is $\mu_0 \tan\delta/\mu'$. Total losses consist of eddy current, hysteresis and residual losses.

Write heads are soft magnetic materials designed for high-frequency use. Typical materials are ferrites, nickel–iron and amorphous alloys, often in the form of thin films. Important parameters are μ, H_s and H_k. Read heads may be inductive or magnetoresistive or use the Hall effect.

4.3 Paramagnetic and Diamagnetic Materials

For the material specification of paramagnetic and diamagnetic materials, magnetic susceptibility is given at the temperature of interest. Pure copper is diamagnetic but often contains iron impurities that contribute a large paramagnetic susceptibility. Aluminum is paramagnetic. Liquid oxygen is strongly paramagnetic. Austenitic steels (AISI types 304, 316 and 321) are paramagnetic but may partially transform to ferromagnetic martensite on thermal cycling to, or mechanical straining at, cryogenic temperatures. Most organic materials are diamagnetic. Lide (1991) gives tables of the molar susceptibilities of the elements and many inorganic and organic compounds.

See also: Demagnetizing Factors; Magnetic Materials: Basic Concepts; Measurements in Magnetic Materials

Bibliography

Bennett L H, Page C H, Swartzendruber L J 1976 Comments on units in magnetism. In: Becker J J, Lander G H, Rhyne J J (eds.) 1976 *Magnetism and Magnetic Materials—1975*, AIP Conference Proceedings, Vol. 29. American Institute of Physics, New York, pp. xix–xxi (reprinted 1978. *J. Res. Natl. Bur. Stand.* 83: 9–12)

Brown W F Jr 1962 *Magnetostatic Principles in Ferromagnetism*. North-Holland, Amsterdam, pp. 1–13

Brown W F Jr 1984 Tutorial paper on dimensions and units. *IEEE Trans. Magn.* 20: 112–17

Brown W F Jr, Frank N H, Kemble E C, Michener W H, Murdock C C, Webster D L 1950 The teaching of electricity and magnetism at the college level. *Am. J. Phys.* 18: 1–25; 69–88

Cohen E R, Giacomo P 1987 Symbols, units, nomenclature and fundamental constants in physics. *Physica A* 146: 1–68

Cullity B D 1972 *Introduction to Magnetic Materials*. Addison-Wesley, Reading, MA, pp. 49–61

International Electrotechnical Commission 1973 *Magnetism*. IEC, Geneva, Publication No. 50(901), Chap. 901

International Electrotechnical Commission 1986 *Magnetic Materials. Part 8: Specifications for Individual Materials*, IEC 404–8. IEC, Geneva, Sects. 1, 6

International Organization for Standardization 1982 *ISO Standards Handbook 2: Units of Measurement*, 2nd edn., ISO 31/V–1979. ISO, Geneva, pp. 85–108

Jackson J D 1975 *Classical Electrodynamics*, 2nd edn. Wiley, New York, pp. 811–21

Lide D R (ed.) 1991 *CRC Handbook of Chemistry and Physics*, 72nd edn. CRC Press, Boca Raton, FL, pp. 9.33–9.104

Maxwell J Clerk 1892 *A Treatise on Electricity and Magnetism*, 3rd edn., Vol. 2. Clarendon, Oxford, pp. 47–78 (reprinted 1954, Dover, New York)
Shadowitz A 1988 *The Electromagnetic Field.* Dover, New York, pp. 294–341
Silsbee F B 1962 Systems of electrical units. *J. Res. Natl. Bur. Stand.* 66C: 137–83 (reprinted 1963, National Bureau of Standards, Washington, DC, Monograph 56)

R. B. Goldfarb
[National Institute of Standards and Technology,
Boulder, Colorado, USA]